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Multi-Gigabits per Second Spatial Multiplexing Transmission Using Passive OFE and WDM-over-POF

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Abstract *Indoor networks should be simple and enable multi-Gbps wireless links at low costs. Spatial multiplexing links from multiple optical access points using WDM-over-POF feeder and passive optical front ends are presented. Using discrete multitone on two colours we can double the throughput to 5.2 Gbps.*

Introduction

With the exponential increase in the amount of wireless data traffic, the radio spectrum is becoming overcrowded. In addition, radio networks have limited use in applications where electromagnetic interference (EMI)-safety is required, as in factory halls, hospital operation rooms, in-flight entertainment/communication, petrochemical plants, and others. Although in the past decades innovations have been made to increase bit rates and densities of the wireless radio networks, the wireless technology required to support these improvements becomes complex [1]. For these reasons, there is a need to search for new spectrum opportunities. One of the main alternatives is the optical wireless communication (OWC), which offers a large bandwidth within the unlicensed optical spectrum. Among the OWC solutions, a promising one is the visible light communication (VLC), a.k.a. light fidelity (LiFi) [2]. LiFi systems are increasingly becoming commercially available and have the advantage of using the already existing light for illumination and communication. However, the current available commercial solutions are mainly focused on communication purposes [3,4].

One of the main challenges of the LiFi systems, is how to carry the data from the residential gateway (RG) to each room, and how to optimize the data densities in a wireless cell [5]. Nowadays, powerline, coax cables and Cat-5 are the commonly used feeder lines for the LiFi systems, but they are not bandwidth nor power efficient. For these reasons, in [6] we proposed to use the 1-mm cores size step-index plastic optical fibres (SI-POFs, a.k.a. standard POF) that are remotely fed by a broadband laser diode (LD), and use the light launched by the fibre end to transmit data. This results in a passive optical front end (OFE) and consequently, no dedicated luminaires are required, as presented in Fig. 1. The main advantage of the proposed system is that the ceiling structure is fully passive, thus no optical-electrical-optical conversion is needed. This brings operational benefits, where no maintenance and electrical powering would be required. This POF is

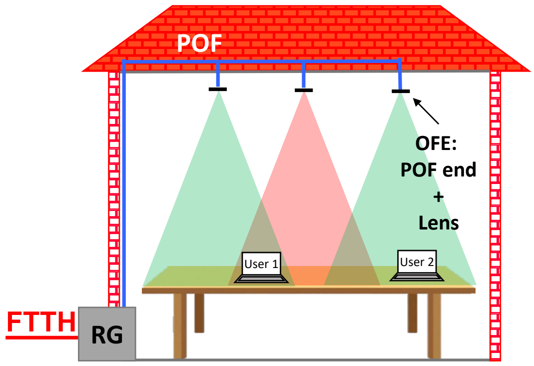

Fig. 1: Indoor network using POFs as feeder line and passive OFE for the wireless link, where only User 1 can be served by the spatial multiplexing due to overlapped coverage.

chosen because of its do-it-yourself technology, EMI-free and small bending radius. In addition, this standard POF works in the visible wavelength, which allows visual link testing and eases the installation. Despite having several advantages, SI-POF has as a major drawback a strong intermodal dispersion that leads to a narrow transmission bandwidth [7]. This drawback can be overcome with the use of spectrally efficient modulation formats, leading to high throughputs. Wavelength division multiplexing (WDM) technique is an attribute to increase a single link performance or to realize distributed multiple-input-multiple-output (D-MIMO) in the wireless link and can be beneficial once it supports user mobility and guarantees consistent link performance [8]. Wireless MIMO can be implemented as spatial diversity (SD) and spatial multiplexing (SM) where the wireless channel condition determines whether SD or SM is used.

In our previous work, presented in [9] we explored the WDM-over-POF concept using SD technique, thus transmitting the same information through multiple channels, and in consequence, improving the system's reliability. In this paper we focus on applying the concept of SM to improve the system's throughput. In our system, we use each colour of the WDM channel to carry different data streams. The data of each channel is part of the original data stream generated in the transmitter.

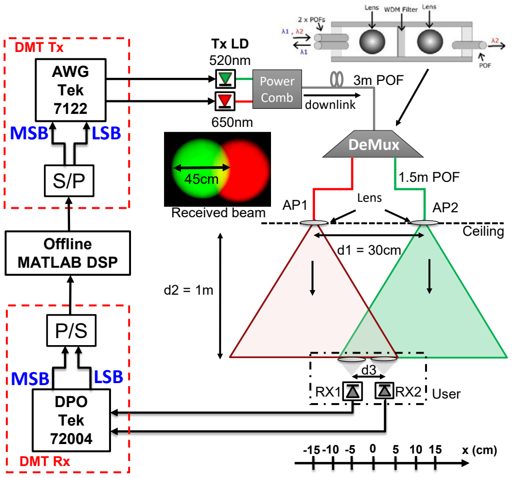

Fig. 2: WDM-over-POF schematic with a 2×2 MIMO VLC link schematic, where the terminal has two receivers: RX1 is aligned to AP1 and RX2 to AP2. M/LSB: most/least significant bits.

When the user is placed in a position that is served by multiple access points (APs), the SM multiplexing concept can be applied, as presented in Fig. 1. In contrast, it is not possible to apply SM to the areas served by only one AP. In addition, we improved the results for the SD concept, where we optimized the system obtaining higher power and consequently increasing SNR and throughput. Our wireless link is composed by a POF-end with a lens placed in a defocused position, consequently increasing the coverage area, and supporting user mobility.

Spatial Multiplexing using WDM-over-POF

In Fig. 1 the proposed concept for an indoor communication network is presented. POFs are used as feeder line to interconnect the RG to each room, where the last meter connectivities are provided by a VLC channel, and the signal emitted from the POF-end is used to transmit data in the wireless link. The light exiting the POF-end is launched by a half angle of 30°, resulting in an extremely divergent beam. This is caused by the large numerical aperture (NA = 0.5) of the used standard POF. Hence, to control the beam divergence and, in consequence, increase the size of the coverage area, a lens must be placed in a defocused position in front of the POF-end.

In Fig. 2, the schematic of the setup is presented. To evaluate the system's performance and achieve high spectral efficiency, the DMT modulation format is used. At the transmitter side the data stream is generated. Once we are working with SM, each channel will carry one part of the original stream. For this reason, the original stream is split in two and each half stream is sent to each of the LDs. The transmitter is composed by two distributed feedback (DFB) LDs, one with emitting wavelength at 520 nm (green), and the other at 658 nm (red) and a 2×1 power combiner. The optical emitting power for the green and red LDs are -1.8 dBm and +2 dBm, respectively. The LDs are directly modulated in their linear region and butt-coupled into the POF. The signal is then combined by the 2×1 power combiner, follows through 3 m POF, and it is then demultiplexed. Once there are not commercially available demultiplexers (DeMux) for POFs, a prototype must be manufactured. Among the different approaches to implement the DeMux we used the one based on 0-degree incidence dichroic filter, as seen in Fig. 2. This approach was chosen due to its low cost, low losses and because it is compact, thus suitable for indoor networks. After the DeMux the signals reach the POF-end, where lenses are placed in a defocused position and a coverage area of 45 cm diameter is created, as shown in Fig. 2. The signal is then received and detected by an optical receiver, composed by a silicon photodiode (PD) and a transimpedance amplifier (TIA). The used receiver has a detection bandwidth of 1.2 GHz, and its sensitivity is wavelength dependent. An important aspect in a DMT transmission is the synchronization of the transmitted and received signal. In this work we use two methods for synchronization. The first is the addition of cyclic prefix (CP) in each stream, that allows to find the start of the DMT frame. Second, the transmitter and receiver clocks are synchronized. This is realized by tracking the phase of each subcarrier after the FFT and correcting it for all the DMT frames. The two streams are then recombined, and an offline signal processing deploys throughput, signal-to-noise ratio (SNR) and BER counting.

Results and discussion

As presented in Fig. 2, the distance between APs (d1) is 30 cm, the vertical distance between APs and receiver (d2) is set as 1 m, and the distance between receivers (d3) is set as 5 cm. At the receiver side, the x-axis represents the user's position. Position 0 is equivalent to the position in the middle of the intersection of AP_1 and AP_2 (POF-end transmitters), where the highest crosstalk level is obtained, and positions -15 and +15 represent, respectively, the position where the user is exactly under AP_1 and AP_2. To simulate user movement, the system's performance is characterized by moving the receiver at various x-positions and measuring the total throughput. For reliable measurements, APs and the user receivers are kept optimally aligned, also when the user moves along the x-axis.

The DeMux prototype, presented as an inset in Fig. 2, has 3.4 dB loss and -13 dB crosstalk for the green channel. For the red channel, a loss of 4 dB and a crosstalk of -28 dB are measured. The channel is estimated with a pilot signal with 64 subcarriers. These subcarriers allow the system to

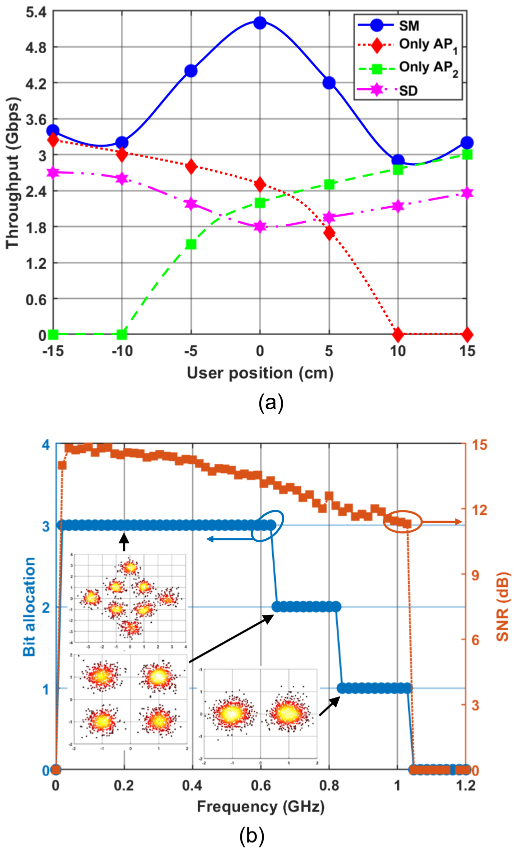

Fig. 3: Link performance of the VLC transmission using WDM-over-POF and applying DMT modulation with a clipping ratio of 8dB (a), bit allocation and received SNR for the user at position 0 (b).

achieve its maximum performance with a bit error rate (BER) value of around 10^{-3}. In this work the concept of SM is applied, thus, in the transmitter side, the signal is generated and split in two streams. Each stream is sent to an arbitrary waveform generator (AWG), that acts as a digital-to-analog converter (DAC). At detection, the signal is received by a photodiode (PD) and amplified by a transimpedance amplifier (TIA), it then follows to a digital phosphor oscilloscope (DPO) that works as an analog-to-digital converter (ADC).

In Fig. 3(a) the results for the throughput are presented for four different settings. The red (diamond) and green (square) lines represent the throughput for the red and green channels respectively. We can see that the throughput increases when the user approaches each AP. Inversely, the throughput becomes lower as the user moves away from APs. The throughput curves should intersect at position 0, but due to the wireless emitting power and receiver sensitivity difference between the red and green channel, the curves cross each other slightly in the green coverage. These differences (red channel has more power and better sensitivity) make all throughput curves somewhat asymmetric as a function of the user position. When the SD concept is applied, pink (star) line we can observe that the throughput becomes minimum in the overlapping area, in the centre at position 0. This drop is associated to destructive interference caused by the different optical paths and the use of two different LDs, which makes it difficult to manage interference. Looking at Fig. 3, blue (solid circle) line, we can obtain higher throughputs with the maximum of 5.2 Gbps at position 0 when SM is applied. For the SM concept each wavelength is transmitting one part of the original stream, and in the overlapping area, the user is receiving signal from both APs and the SNRs are still relatively good to generate higher throughputs than other settings. At positions -15 or +15, the user is receiving signals from either AP_1 or AP_2, making our SM concept is less effective to be deployed. Therefore, the performance is similar to the single AP setting (< 3.4 Gbps) and slightly better than SD (< 2.7 Gbps). In Fig. 3(b) the received SNR and bit allocation, for the user at position 0, are presented. Furthermore, in Fig. 3(b) the constellation, for each bit allocation level, is presented as an inset, and a clear separation between the QAM levels can be seen, indicating excellent performance of the system.

It is important to highlight that we are working with eye-safe LDs for POF links and due to additional losses in the link, APs emit much lower optical power towards the receiver. Increasing the wireless power to the eye-safety level will allow us to scale up the system to have longer POF and wireless links.

Conclusions

In this paper a novel concept for indoor communication employing POF as the feeder line and passive OFEs instead of active luminaires was presented. An OFE consists of a POF-end and a lens in a defocused position. We applied with two APs the SM concept in the wireless link, which allowed to improve the link throughput. The results were given for the downlink using two channels: 520 nm and 658 nm. The throughput was characterized using DMT. We showed that when a user is in the overlapping coverage of two APs, using SM can double the throughput to 5.2 Gbps, which is much higher than SD. The proposed concept, where POFs are employed as the feeder network and data is transmitted by the light launched from the POF using either SM or SD technique considering the wireless channel property, is an attractive solution to realize high-capacity indoor wireless systems and potentially low cost.

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